The Effects of Temporal and Spatial Variability on Monitoring Agricultural Nonpoint Source Pollution

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ABSTRACT

The Saline Valley Rural Clean Water Program project was one of 21 projects developed to evaluate methods of controlling agricultural nonpoint source pollution. Control programs were designed around voluntary implementation of best management practices, and water quality trends were monitored at eight stream stations from July 1981 to December 1989, using a fixed, weekly sampling design. An additional monitoring program was established within the Macon Creek subbasin (Station 9) in June 1988 to quantify temporal and spatial variability in pollutant loads. Macon Creek was monitored daily for seven days following any storm of more than half an inch of rain. Five stations were added upstream from existing Station 9 to examine spatial variation in loading rates throughout the subbasin. This study describes these storm monitoring results and discusses their implication to the Saline project's monitoring data.

Saline Valley was one of 21 projects within the U.S. Department of Agriculture's Rural Clean Water Program (RCWP) designed to evaluate methods for controlling agricultural nonpoint source pollution. For meaningful results from a water quality management perspective, it is necessary to quantify the effectiveness of best management practices (BMPs) in reducing pollutant loadings associated with agricultural production. Most projects found it difficult to establish these relationships for treatment applied at the watershed level.

Measuring effectiveness was complicated because a wide variety of BMPs were adopted gradually over large areas of land and because the RCWP relied on voluntary participation, which greatly limited control over the timing, amounts, and placement of these practices. The lack of treatment control, the spatial scales involved, and the inherent variability of meteorological processes posed significant problems for the water quality monitoring programs.

Limited funding and human resources severely restricted the Saline Valley project's ability to address patterns of temporal and spatial variability. The two most significant problems were the lack of continuous discharge records and the inability to monitor individual storm events in detail. The purpose of this project was to quantify patterns of temporal and spatial variability within the watershed by monitoring individual storms daily and increasing the number of stations along the stream. These data were then used to help evaluate and interpret the monitoring data. Data presented in this discussion predominately focus on results from Subbasin 9, where all of the additional monitoring took place (Fig. 1.).

Materials and Methods

Temporal Variability

Temporal variability in pollutant loading was assessed on annual and daily time scales. Loading data collected under the project's weekly sampling scheme were tabulated and analyzed graphically through cumulative loading distributions to examine annual variability. Daily variability was assessed by monitoring individual storm events; however, only rainstorms producing greater than 0.5 inches a day were sampled. Following a storm, Macon Creek transect stations were monitored daily for seven days or until discharge returned to baseline conditions. A total of eight storms were monitored between 1988 and 1989.

Storm monitoring results were used to quantify potential errors in the project's loading estimates. Errors in the project's weekly loading estimates were calculated from the difference between summing the seven consecutive daily measurements versus extrapolating a single sampling event over a week. Errors were calculated for each of the seven days following a storm to represent all possible intervals between the storm and sampling day of a fixed schedule.

Results from storm monitoring were also used to evaluate errors in annual loading estimates. A daily precipitation record, obtained from the Saline wastewater treatment plant, was used in conjunction with average loading values observed for storms to estimate annual loads. These computed loading values were then compared against the project's loading estimates.

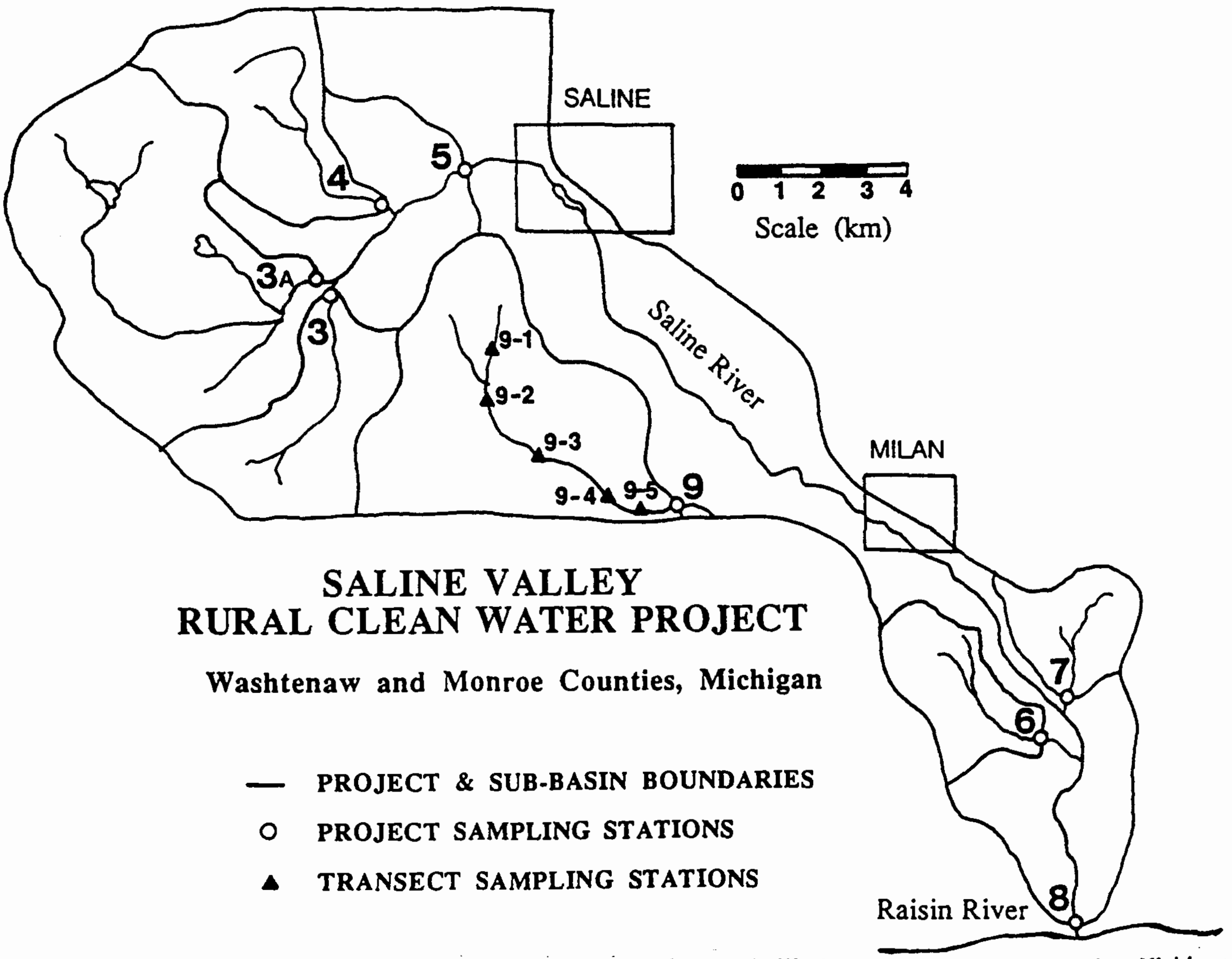

Figure 1.—Saline Valley Rural Clean Water Project study area located in Washtenaw and Monroe counties, Michigan. Project stations were located at (3) Saline–Bridgewater Drain, (4) Bauer Drain, (6) Bear Creek, (7) Wanty Drain, and (9) Macon Creek. Stations 3A, 5, and 8 were located on the Saline River. Transect Stations 9-1 to 9-5 were added along Macon Creek to examine patterns in spatial variability.

Spatial Variability

Spatial variability was examined over both watershed and subbasin scales. Variability within the project's watershed was evaluated by comparing patterns in concentration, loading, and export rates among the stations. Variability at the subbasin level was examined by creating a longitudinal transect along Macon Creek within Subbasin 9 (Fig. 1). Five additional stations were added upstream of existing Station 9, ranging from 0.8 to 2.9 kilometers apart. Transect stations were established in September 1988 and sampled during routine project sampling and storm events until the project's termination in December 1989.

Results

Temporal Variability in Pollutant Loading

The project's annual loading data for Station 9 revealed extreme variability in both magnitude and timing. Annual loads for suspended solids, total phosphorus (total-P), soluble phosphorus (soluble-P), and nitrate (NO_3) varied by 14-, 5-, 7-, and 3-fold, respectively, over the course of the study (Table 1). Cumulative loading distributions for total phosphorus revealed that loading rates were highly variable within a given year as well as among years (Fig. 2). If loading rates were uniform throughout the year, distributions would plot as straight lines. Distributions were highly nonlinear and indicated that annual loads were dominated by a storm events. Summing the three highest weekly loading estimates from the project's data indicated that, on average, 76, 56, 51, and 50 percent of annual loads for suspended solids, total-P, soluble-P, and nitrate, respectively, occurred in only 8 percent of the time within 28 days of the year.

Table 1.—Annual loads for suspended solids (SS), total phosphorus (TP), soluble phosphorus (Sol-P), and nitrate (NO_3) at Station 9 for 1983 through 1989.

	ANNUAL LOAD (mtons)			
YEAR	SS	TP	SOL-P	NO_3
1983	248	0.49	0.15	15.8
1984	101	0.34	0.15	13.6
1985	79	0.27	0.09	18.6
1986	256	0.85	0.26	19.8
1987	43	0.20	0.07	15.3
1988	604	1.13	0.49	44.4
1989	342	0.71	0.29	34.1

Daily monitoring of individual storm events revealed that the majority of loading occurred within

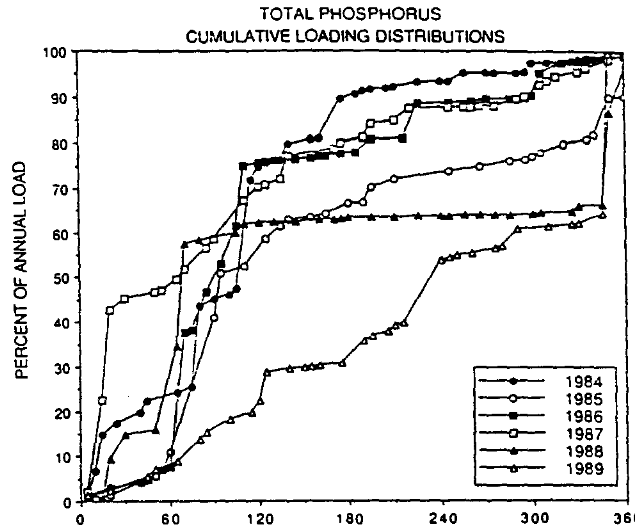

Figure 2.—Total phosphorus cumulative loading distributions at Station 9 for years 1984 through 1989.

the first 48 hours of a storm and returned to baseline conditions within three days (Table 2). This response was fairly consistent for all storms monitored, which ranged from 0.5 to 2.5 inches per day of precipitation. The percentage of the week's load, which occurred on Day One after a storm, was always greater for particulate parameters than for dissolved nutrients or discharge levels. On average, 40, 85, 71, 65, and 55 percent of the week's total load for discharge, suspended solids, total-P, soluble-P, and nitrate, respectively, occurred on this first day (Table 2). This pattern reflects a "first flush" effect, where material that has accumulated on the ground is washed off by overland runoff during the first part of a storm. Nitrate showed the smallest loading spike because its concentrations tended to peak one or two days after the storm when overland runoff ceased and the majority of input to the stream was derived from seepage through the soil.

Table 2.—Percent of weekly discharge (DIS), suspended solids (SS), total phosphorus (TP), soluble phosphorus (Sol-P), and nitrate (NO_3) loads occurring over seven days following a storm.

# DAYS AFTER STORM	PERCENT OF WEEKLY LOAD				
	DIS	SS	TP	SOL-P	NO_3
1	40	85	71	65	55
2	20	9	15	14	15
3	13	2	5	10	10
4	9	1	3	5	8
5	7	1	3	3	7
6	6	1	2	2	3
7	5	1	1	1	2

Results from daily sampling were used to calculate loading errors produced under the project's fixed weekly sampling schedule. Errors in weekly loading estimates varied as a function of the duration between the storm event and sampling (Table 3). If sampling occurred during the first 24 hours after the storm, weekly loads were overestimated by an average of 505, 405, 365, and 295 percent for suspended solids, total-P, soluble-P, and nitrate, respectively. Errors were greater for particulate species because a larger percentage of their weekly load occurred on Day One after storms. Conversely, when sampling occurred five or more days after the storm, weekly loads were underestimated by approximately 93 percent for suspended solids, 79 percent for total and soluble phosphorus, and 50 percent for nitrate.

Table 3.—Percent loading error for suspended solids (SS), total phosphorus (TP), soluble phosphorus (Sol-P), and nitrate (NO_3) based on extrapolating a single sampling event over seven days versus sampling daily for seven days.

# DAYS AFTER STORM	PERCENT ERROR IN WEEKLY LOAD			
	SS	TP	SOL-P	NO_3
1	505	405	365	295
2	-36	+/-	+/-	+/-
3	-86	-64	-29	-29
4	-93	-79	-64	-43
5	-93	-79	-79	-50
6	-93	-86	-86	-79
7	-93	-93	-93	-86

The implications of this sampling bias were used to evaluate the project's annual loading estimates. Average loading values from storm monitoring were substituted for existing project estimates when more than 0.5 inches of rainfall occurred. Average weekly loading values following storms were 50,000, 60, 15, and 1,700 kilograms for suspended solids, total-P, soluble-P, and nitrate respectively. On average, rainfall of 0.5 or greater occurred 25 days per year in the project area. Adjusted loads indicated that only 3, 13, 20, and 17 percent, respectively, of the annual loads occurred from outside these storms. More importantly, adjusted loads indicated the project measured only 19, 34, 47, and 46 percent of the annual loads for suspended solids, total-P, soluble-P, and nitrate respectively (Table 4).

Table 4.—Project's loading estimate (observed) versus adjusted loading estimate based on storm monitoring results (predicted) for suspended solids, total and soluble phosphorus, and nitrates at Station 9.

MEAN ANNUAL LOAD	SUSP. SOLIDS (mton)	TOTAL-P (kg)	SOL-P (kg)	NITRATE (mton)
Observed:	240	590	220	24
Predicted:	1,295	1,725	470	52
Percent observed:	19%	34%	47%	46%

Spatial Variability in Pollutant Loading

Areal normalized export rates revealed large differences in loadings patterns among the project's subbasins (Table 5). Rates varied the most for suspended solids (eightfold) and least for soluble-P (twofold). Differences among basins were specific to individual parameters. For example, in Subbasin 7, suspended solid export was nearly sixfold less than in Subbasin 3 but nitrate export was nearly sixfold greater (Table 5).

Table 5.—Export rates for runoff, suspended solids, total and soluble phosphorus, and nitrate calculated as annual mean load divided by watershed size.

STATION	AREA (ha)	RUNOFF (cm)	EXPORT RATE (kg/ha/yr)			
			SS	TP	SOL-P	NO_3
3	1,610	20	193	0.29	0.07	8.0
4	1,980	19	183	0.28	0.08	26.7
5	11,780	33	267	0.38	0.09	12.0
6	1,000	30	33	0.26	0.11	19.4
7	780	61	31	0.26	0.06	44.5
8	31,200	28	106	0.50*	0.21	10.2
9	3,940	10	61	0.15	0.06	6.0

*After subtracting known point source contributions.

Regression of annual mean total-P concentration versus annual mean discharge also indicated that subbasins responded differently (Fig. 3). Subbasin streams exhibited similar phosphorus concentrations during years with lower mean discharge; however, as mean discharge increased, concentrations varied greatly, as indicated by the different slopes. Station 9 showed the greatest increase in phosphorus concentration whereas Station 5 showed only a minimal response. Variations in response could have resulted from differences in the physical characteristics of the basins and in current land use activities that would affect source amounts and transport efficiencies.

To examine spatial variability at the subbasin level, a longitudinal transect was created along Macon Creek (Fig. 1). Concentration patterns were examined to evaluate whether individual farm sites were having a disproportionately large effect on pollutant loads and survey changes that occur during transport. Differences among transect stations were examined statistically using a nonparametric Kruskhal-Wallace test (Table 6). Data were stratified according to low-flow and stormflow conditions. Concentration patterns were quite similar throughout the transect under both conditions. Surprisingly, more significant differences occurred for total-P, soluble-P, and ammonia concentrations under low-flow versus stormflow conditions. These results imply that internal cycling during transport affected

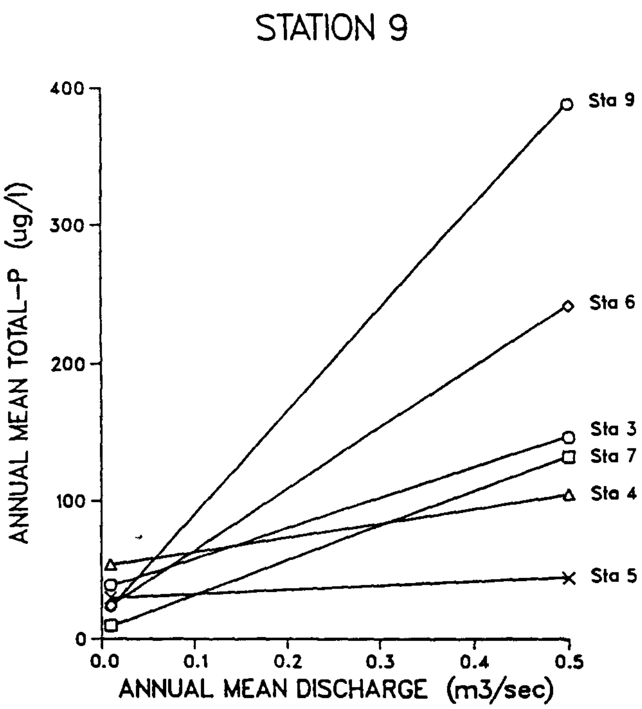

Figure 3.—Annual mean total phosphorus concentration plotted against annual mean discharge for each subbasin within the Saline Valley watershed. Regressions were based on means from 1982 through 1989 and were all significant at the 0.05 level.

concentration patterns more than differences in input from runoff. Presumably the slower velocities and less turbid water during low-flow conditions allowed sufficient time for biogeochemical processes to alter concentration patterns. Under stormflow conditions, only nitrate and chloride showed consistent differences between stations. These results are interesting because inputs for both these parameters tended to be dominated by subsurface flows.

Discussion

Temporal Variability

Temporal variability in loading rates over daily and annual scales were examined to evaluate the reliability of the project's monitoring design. Cumulative load distributions revealed that a significant portion of the annual load occurred in only a few sampling intervals. Specifically, over 75 percent of the suspended solids and 50 percent of the total and soluble phosphorus annual loads were received in 8 percent of the time.

The significance of a few individual storms to annual loads has also been observed in previous studies (Taylor et al. 1971; Johnson et al. 1976) and

Table 6.—Kruskal-Wallace test for concentration differences among Macon Creek transect stations during stormflow and baseline conditions (N=58 and 61 respectively) (Alpha < 0.1 reported as NS).

PARAMETER	STORMFLOW					BASELINE				
	STA:	9-3	9-4	9-5	9	STA:	9-3	9-4	9-5	9
	9-2	NS	NS	NS	NS	9-2	.09	.01	.06	NS
TOTAL-P	9-3		NS	NS	NS	9-3		NS	.00	NS
	9-4			NS	NS	9-4			.00	.02
	9-5				NS	9-5				NS
	STA:	9-3	9-4	9-5	9	STA:	9-3	9-4	9-5	9
	9-2	NS	.08	NS	NS	9-2	NS	NS	NS	NS
SOLUBLE-P	9-3		NS	NS	NS	9-3		NS	.03	NS
	9-4			NS	NS	9-4			.00	.03
	9-5				NS	9-5				NS
	STA:	9-3	9-4	9-5	9	STA:	9-3	9-4	9-5	9
	9-2	.00	.00	.00	.00	9-2	.00	.00	.00	.00
NITRATE-N	9-3		.07	.01	.00	9-3		NS	.00	.01
	9-4			NS	.04	9-4			.00	NS
	9-5				NS	9-5				NS
	STA:	9-3	9-4	9-5	9	STA:	9-3	9-4	9-5	9
	9-2	NS	.08	NS	NS	9-2	.00	.01	NS	NS
AMMONIA-N	9-3		NS	NS	NS	9-3		NS	.03	NS
	9-4			NS	NS	9-4			.01	.02
	9-5				NS	9-5				NS
	STA:	9-3	9-4	9-5	9	STA:	9-3	9-4	9-5	9
	9-2	NS	NS	NS	NS	9-2	NS	NS	NS	NS
SILICA	9-3		NS	NS	NS	9-3		NS	NS	NS
	9-4			NS	NS	9-4			NS	NS
	9-5				NS	9-5				NS
	STA:	9-3	9-4	9-5	9	STA:	9-3	9-4	9-5	9
	9-2	NS	NS	.05	.00	9-2	NS	NS	NS	.02
CHLORIDE	9-3		NS	NS	.00	9-3		NS	NS	.03
	9-4			NS	.02	9-4			NS	.02
	9-5				.07	9-5				.01

appears quite characteristic of nonpoint source pollution. The magnitude of loads following storms is great because the effect of increased discharge is multiplied by that of increased concentration. The magnitude and duration of increased concentration appears to be a function of the amount of pollutant that has accumulated in the watershed and the rate at which it is washed off. Daily monitoring data of storm runoff indicated that loading spikes typically lasted only a few days. Spikes were always greatest for particulate species, reflecting the effect of increased erosion from overland runoff and probably the increased carrying capacity of the stream during higher velocities. Dissolved nutrient concentrations remained elevated for several days after the storm ended, presumably because of subsurface inputs, and consequently, daily loading rates decreased more slowly.

The importance of these few large storms to total annual loads implies that BMPs must be designed to handle runoff conditions that develop under intense storms. If BMPs are not effective against these major events, they may reduce only an insignificant portion of the annual loads.

During each study year, annual loads were dominated by a few events. The timing and frequency of these loading spikes were, however, highly variable among years. These results imply that errors in loading estimates using a fixed sampling schedule would be inconsistent between years. Inconsistent errors will compound the problem of high variability resulting from meteorological conditions and could invalidate a monitoring program's conclusions about BMP effectiveness.

Monitoring data from individual storm events revealed that the project's annual loading estimates were extremely inaccurate and could not be used to assess the effects of the land treatment program. The magnitude of variability revealed by this study strongly suggests a mandate for continuous discharge meas- urements and event-based sampling to accurately evaluate nonpoint pollution loading. In addition, the effects of varying amounts of discharge must be removed from annual loading or concentration trends to provide a sensitive measure of land treatment effectiveness. In an earlier analysis of the project's data, changes in empirical regressions of concentration versus discharge were examined to evaluate whether BMPs reduced pollutant export (Johengen et al. 1989). No significant effects were found, and it was concluded that there was insufficient coverage of BMPs. Present results also suggest that sampling biases could have affected concentration and discharge regressions, greatly reducing their sensitivity.

Comparisons between storm event sampling and fixed weekly sampling indicated that the fixed schedule produced extreme errors in loading estimates because the fixed schedule assumed that loading rates were constant over the entire duration between sampling intervals. Daily monitoring indicated loading spikes lasted only a few days; therefore, loads were overestimated if sampling occurred within one or two days after the storm and underestimated if more than two days passed before sampling. This timing also meant that the weekly sampling schedule would often miss the loading from a storm completely. The final result was that the project's annual loading estimates were only 19 to 47 percent of calculated loads accounting for storms.

Stevens and Smith (1978) found that even with load rating curves and continuous discharge measurements, an eight-day fixed sampling schedule underestimated nitrate loading by 18 percent and overestimated particulate-P loading by 43 percent. Errors are produced even when using rating curves because concentration values are predicted from relationships with discharge, and the fixed schedule tends to oversample more common low-flow conditions. Johnson (1979) suggested that, in the absence of automated samplers that can sample on a flow-proportioned schedule, a varying frequency schedule should be used that samples all stages of flow. Sharpley et al. (1976) reported that sampling intervals for some streams should be as short as 60 minutes during peak flow to produce loading estimates with less than a 15 percent error. Resources were not available in this study to examine loading patterns at such time scales.

Spatial Variability

The RCWP was unique because it attempted to establish relationships between land treatment practices applied at the watershed level and resulting changes in the water quality of receiving waterbodies. Few projects, however, addressed the issue of spatial variability within their watersheds. Several projects concurred that sampling within the subbasin helped in examining the relationship between land treatment and water quality (Natl. Water Qual. Eval. Proj. 1989). Results were not, however, discussed in terms of the variability in response among subbasins or the implications for site-specific effects.

This study revealed extreme variability in pollutant export rates among subbasins; differences were specific to the individual parameters. Systematic differences in concentration and loading patterns among subbasins can occur as a result of their size, topography, soil type, land use, and drainage efficiency (Baker, 1985). These findings imply that individual subbasins may respond quite differently to the applied land treatment, and BMP effectiveness should be assessed at the subbasin scale. Monitoring at the subbasin level also establishes stations closer to the sites of BMP implementation and can reduce the influence from nonparticipating areas or other sources of pollution.

Transect stations established within Subbasin 9 revealed that internal cycling within the stream can also affect concentration patterns. These results also imply the need to monitor water quality trends as close to the site of land treatment as possible. Although transect stations did not reveal many significant differences in pollutant inputs during storms, they did catch occasional spikes that were orders of magnitude different. These site-specific results could help target critical areas within the subbasin.

Variations in loading rates among basins could be used to focus attention on those areas that may have the greatest effect on water quality. Targeting critical areas was expounded as the best way to maximize cost-effectiveness (Natl. Water Qual. Eval. Proj. 1989). One difficulty with this approach is that extensive mon- itoring must take place before the land treatment program can be initiated. However, although this degree of initial monitoring could ultimately make BMPs more cost effective, it may be difficult to convince managers to invest in this approach.

Conclusions

Temporal and spatial variability in pollutant loadings were extremely high throughout the study. Cumulative loading distributions indicated that a few storms can produce over 50 percent of the total annual pollutant load. Loading spikes typically lasted only a few days; therefore, their impact was often missed because the project mandated weekly sampling. Loading adjustments based on a daily precipitation record indicated that the project estimated only 20 of the suspended solids load and 50 percent of the total and soluble phosphorus load. Storm monitoring results suggest that a continuous discharge record and flow-proportional sampling are necessary to establish accurate loading estimates for nonpoint source pollution. Without this detailed record, evaluating long-term trends would be impossible, given the extreme temporal variability.

Differences in concentration and loading patterns among the project's stations revealed a high degree of spatial variability within the watershed. For transect stations established along Macon Creek, variability was greater during low-flow versus stormflow conditions. Results suggest that monitoring at the subbasin level would help target critical areas and improve chances of detecting water quality changes resulting from land treatment application.

ACKNOWLEDGMENT: This paper is Contribution No. 804 of the Great Lakes Environmental Research Laboratory.

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United States
Environmental Protection
Agency

Office of Research and Development
Office of Water
Washington, DC 20460

EPA/625/R-92/006
August 1992

EPA

Seminar Publication

The National Rural Clean Water Program Symposium

10 Years of Controlling Agricultural Nonpoint Source Pollution: The RCWP Experience